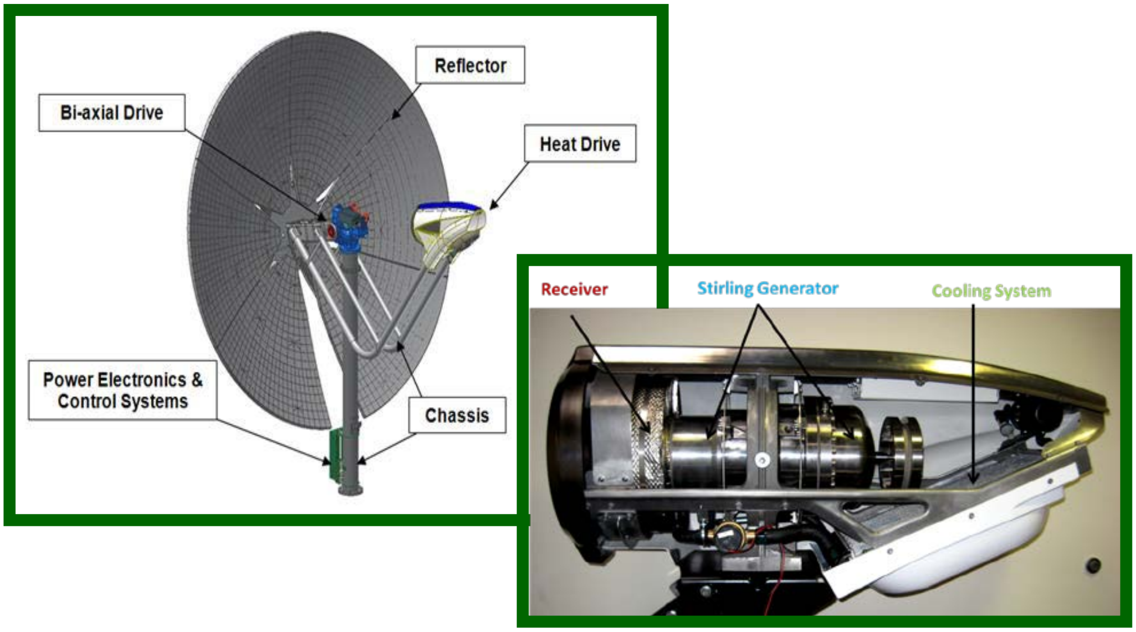
ESTCP
Cost and Performance Report

(EW-201145)



Combined Heat & Power Using the Infinia Concentrated Solar - CHP PowerDish System

August 2013

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **AUG 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**
4. TITLE AND SUBTITLE **Combined Heat & Power Using the Infinia Concentrated Solar - CHP PowerDish System**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**51**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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ACRONYMS AND ABBREVIATIONS

AIRR	adjusted internal rate of return
AWG	American wire gauge
BTEL	building thermal energy loop
BTU	British thermal unit
CHP	Combined Heat and Power
CO_2	carbon dioxide
CSU	Colorado Springs Utilities
DNI	direct normal irradiance
DoD	Department of Defense
DPW	Directorate of Public Works
EIA	Energy Information Agency
EO	Executive Order
ESTCP	Environmental Security Technology Certification Program
f^2	square foot
FOB	forward operating base
FPSE	Free Piston Stirling Engine
GHG	greenhouse gas
IOU	investor-owned utility
kW	kilowatt
kWac	kilowatt alternating current
kWdc	kilowatt direct current
kW_e	kilowatt electric
kWh	kilowatt hour
kWh_e	kilowatt hour electric
kWh_{th}	kilowatt hour thermal
kW_{th}	kilowatt thermal
m^2	square meter
MMBTU	million British thermal units
mWh	megawatt hour
MILCON	Military Construction
NREL	National Renewable Energy Laboratory
OI	over insolation
O&M	operations and maintenance
OMB	Office of Management and Budget

ACRONYMS AND ABBREVIATIONS (continued)

POU	point-of-use
PUC	Public Utility Comission
PV	photovoltaic
RPS	renewable portfolio standard
SIR	savings to investment ratio
TMY	typical meteorological year
W	watt
Wdc	watt direct current

ACKNOWLEDGEMENTS

Thanks to the Department of Defense's (DoD)-Environmental Security Technology Certification Program (ESTCP) for providing funding for this project.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The Infinia PowerDish™ Combined Heat and Power (CHP) demonstration was intended to showcase and assess the capabilities of the Infinia PowerDish CHP technology to generate clean solar electricity as well as thermal energy for domestic hot water and space heat requirements. When applied to Department of Defense (DoD) facilities, at both domestic facilities and forward operating bases (FOB), the PowerDish CHP could reduce the consumption of utility electricity and fossil fuels, thus reducing air and carbon emission pollution as well as stabilizing or even reducing total energy costs for the application site. An alternative to the PowerDish CHP technology for providing non-fossil fuel electric generation and thermal energy for end-use application would be to install two systems: a photovoltaic (PV) system for electricity and a solar thermal system for water and space heating applications. Each of the specific performance objectives was addressed in the demonstration which included: monitoring estimated facility energy usage; maximizing renewable energy usage; maximizing savings for systems economics; minimize direct greenhouse gas (GHG) emissions; monitoring facility metering; monitoring system maintenance; and monitoring system integration. Overall, the demonstration clearly confirmed that the PowerDish CHP technology can provide clean solar electricity as well as thermal energy for water and space heating applications. However, while the amount of electric production was somewhat less than expected, the quantity of thermal energy delivered to the facility for end-use applications was significantly lower than expected. This report and the Final Report detail the reasons for the thermal energy underperformance as well as the lessons learned and performance improvements gleaned from this demonstration.

TECHNOLOGY DESCRIPTION

The PowerDish CHP system is a modified Infinia PowerDish solar system. The Infinia PowerDish solar system uses Infinia's free-piston Stirling generator placed at the focal point of a concentrator dish. The solar energy falling on the mirrored concentrator dish is focused on the hot end of the Stirling generator. Through the Stirling energy cycle and a linear alternator, that solar energy is converted into electricity that can be injected into the utility electric grid. The excess energy from the Stirling cycle is rejected to the air through a closed loop cooling system (much like the cooling loop in a car). To capture the rejected energy from the Stirling cycle and make it available for water and air heating in a nearby facility, a heat exchanger was added to the Infinia PowerDish cooling loop system: the PowerDish CHP. The liquid-to-liquid heat exchanger, mounted on the PowerDish heat drive, was also connected to a closed loop system that carried the heat transferred across the cooling loop heat exchanger to a nearby building where the thermal energy was used for space and water heating. In this way, some of the thermal energy that was "thrown away" by the Infinia PowerDish was captured by the heat exchanger in the PowerDish CHP and injected into the building heat loop for use in heating water and air in the facility, Building #9246 at Fort Carson. This CHP technology and the building point-of-use (POU) hardware are discussed in more detail in the final report.

DEMONSTRATION RESULTS

Over the test period of January 17, 2012 through December 31, 2012, the PowerDish CHP produced 4315 kilowatt hours (kWh) of electricity (kWh_e) and produced 11,109.7 kWh of thermal energy (kWh_{th}) measured at the engine heat exchanger. The demonstration confirmed that the PowerDish CHP can deliver both electric and thermal energy to a facility from a single solar system. Due to PowerDish CHP forced outages and Infinia control system changes, this measured output was about 22% lower than the predicted output of 5500 kWh_e for electricity and about 30% lower than the predicted output of 16,000 kWh_{th} for thermal energy production at the Fort Carson site. In total, the PowerDish CHP provided 54% of the actual electricity and 6% of the actual thermal energy used by the Fort Carson facility.

Very shortly after startup, Infinia identified a potential problem with the high cooling loop temperatures needed for the CHP applications. Infinia ordered the lowering of the cooling loop temperature from the planned 70EC to 60EC maximum and made control system changes that effectively lowered the output of the system by about 10%. This resulted in lower heat transfer to the building heat loop than planned.

During the first winter months of the demonstration, the heat energy transferred to the building and used for space heating was well below expectations. Infinia redesigned and implemented changes to the building heat loop system before the winter season 2012-2013 which resulted in an approximately 350% improvement in heat delivered for space heating.

IMPLEMENTATION ISSUES AND LESSONS LEARNED

The demonstration project experienced several implementation issues which are explained in detail later in the report but include:

- Initial grid interconnection software incompatibility with utility interconnection process,
- Low thermal energy delivery to in-building applications (space heating and water heating), and
- Unexpected PowerDish failures due to design implications from the CHP application.

Some lessons learned for improving the application of PowerDish CHP to future projects include:

- A low-temperature heat exchanger (more surface area) should be utilized in order to provide more heat to the building;
- The Solar CHP system should be kept close to the building and POU applications to minimize losses;
- Thermal heat should be taken directly to the POU applications first and then to storage to maximize the utilization of available thermal energy; and

- An improved design PowerDish that enables 70EC generator cooling loop temperature should be used to improve efficiency of heat transfer to building and POU applications.

1.0 INTRODUCTION

The Infinia Combined Heat and Power (CHP) project, Environmental Security Technology Certification Program (ESCTP) Project EW-201145, was hosted by the Department of the Army at Fort Carson, Colorado and demonstrated CHP generation via clean, solar thermal resources using a modified version of Infinia's PowerDish System. This demonstration was conducted between January 17, 2012 and December 31, 2012 following the testing, installation and startup commissioning events that took place during October through December 2011.

1.1 BACKGROUND

The PowerDish CHP technology, as installed, demonstrated thermal and electric energy production compatible with both domestic and forward operating base (FOB) power, domestic hot water and space heat requirements. The technology's benefits will help the Department of Defense (DoD) achieve its objectives of reductions in the energy production burden, fuel transport costs and logistics, and greenhouse gas (GHG) emissions.

Infinia Corporation has been developing the Free Piston Stirling Engine (FPSE) for military, commercial, and space applications for almost 30 years. As Infinia developed a commercial product for its FPSE operating on solar energy for electricity production, called the PowerDish™, a reasonable extension for the commercial product was to capture the heat that otherwise was rejected to air through a closed-loop radiator system for use in local space heating and hot water applications. ESTCP Project EW-201145 enabled Infinia and its host site, Fort Carson, to demonstrate the effectiveness of such a system and to access improvements that could enable such a system, when commercial, to find application not only at commercial sites but in military base and FOB applications.

The default DoD technology option for providing solar electricity as well as solar thermal energy is to install 2 systems. A photovoltaic (PV) system would be installed to provide the electricity while a separate solar thermal system would be installed to provide hot water to a facility. The PowerDish CHP demonstration evaluates the potential to provide both electricity and thermal energy from a single system. The PowerDish CHP system has the potential to provide the energy desired at a lower total cost. If successfully deployed commercially, the PowerDish CHP can provide economic benefits and improved energy security as well as the potential for reduced loss of life in FOBs.

1.2 OBJECTIVES OF THE DEMONSTRATION

The specific performance objectives of the demonstration included:

- Monitor estimated facility energy usage;
- Maximize renewable energy usage;
- Maximize savings for systems economics;
- Minimize direct GHG emissions;
- Monitor facility metering;
- Monitor system maintenance; and
- Monitor system integration.

Each of these performance objectives were addressed in the demonstration and the success criteria are detailed in the Final Report. In summary, the facility used 47% less electricity than predicted but 105% of the propane predicted. The project demonstrated that the PowerDish CHP can generate clean solar thermal and electric energy compatible with domestic and FOB power, domestic hot water, and space heat requirements. While the level of renewable energy production performance fell 22% (electric) and 30% (thermal) below predictions (and consequently GHG emissions were similarly below prediction), the causes of the under-performance (lessons learned) were identified. The PowerDish CHP system provided 54% of the electricity used by the facility, but only 6% of the thermal energy consumed by the building. The low level of thermal energy delivered to the building to offset propane usage was notable. Importantly, a redesign of the building loop operation demonstrated that significantly more energy can be delivered during periods of thermal energy demand. This and other lessons learned can be used to improve future installations so they are more effective at a lower total cost. This PowerDish CHP demonstration confirms, for the DoD, that the PowerDish CHP system can provide both electric and thermal energy to a facility without the need for two separate solar systems.

This demonstration also provided insights to Infinia to make design changes so that future, commercial versions of the PowerDish CHP will provide better thermal heat quality and transfer to external facility heat loops.

1.3 REGULATORY DRIVERS

According to Executive Orders (EO) 13423 and 13514, it is DoD's policy to improve energy conservation and efficiency, reduce energy and water demand, and increase the use of renewable energy to improve energy flexibility, save financial resources, and reduce emissions that contribute to air pollution and global climate change. DoD has also established a goal of 25% renewable energy by 2025, including requirements, under the Energy Independence and Security Act of 2007, for the production of 30% of hot water in new and renovated federal buildings from solar sources.

Additionally, Colorado became the first U.S. state to create a renewable portfolio standard (RPS) by ballot initiative when voters approved Amendment 37 in November 2004. Updates and expansions to the law were adopted in March 2007 (HB1281) and in 2010 (HB1001). Eligible renewable-energy resources include solar-electric energy. The Public Utility Commission (PUC) has issued and amended rules, as required, to implement the RPS. While the PUC's rules generally apply to investor-owned utilities (IOU), the PUC has provided separate requirements for electric cooperatives and municipal utilities, like Fort Carson's utility provider, Colorado Springs Utilities (CSU). CSU is required to provide the following percentage as renewable energy:

- 3% of its retail electricity sales in Colorado for the years 2011-2014;
- 6% of its retail electricity sales in Colorado for the years 2015-2019; and
- 10% of its retail electricity sales in Colorado for the year 2020 and each following year.

Also, to assist in meeting the renewable requirements and to enable deployment of solar-electric systems in Colorado, House Bill 1160, enacted in March 2008, requires CSU (and all other

municipal utilities with more than 5000 customers and all cooperative utilities) to offer net-metering. The law allows residential systems up to 10 kilowatts (kW) in capacity and commercial and industrial systems up to 25 kW to be credited monthly at the retail rate for any net excess generation their systems produce. Fort Carson was able to use a "net metering" tariff from CSU which enabled the project to generate electricity and put it directly into the Fort Carson distribution network to be consumed on site without any metering by the utility. This PowerDish-generated-electricity directly reduced the electricity that would have been supplied by the utility. In compliance with the regulations implementing the net metering law, the PowerDish CHP system was required to meet the grid interconnection requirements of the utility in order to connect to the electrical grid at Fort Carson.

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2.0 TECHNOLOGY DESCRIPTION

At the time of this ESTCP project selection, Infinia Corporation had developed the Infinia Power Dish, a concentrated solar thermal technology utilizing a highly reliable FPSE with a parabolic dish that produced 3 kW electric (kW_e) of power and 7 kW thermal (kW_{th}) of usable heat. The PowerDish CHP system demonstrated in this project was an Infinia PowerDish modified by adding a liquid-to-liquid heat exchanger to the PowerDish cooling loop. The PowerDish, its development, and the PowerDish CHP development are discussed below.

2.1 TECHNOLOGY OVERVIEW

2.1.1 Infinia PowerDish

The Infinia PowerDish system, which is an electric only system, is made of a:

- Concentrator that collects and focuses the sun to a point;
- FPSE that:
  - Receives the focused solar energy in the hot-end of the engine; and
  - Provides single phase electricity from the linear alternator within the hermetically sealed engine system;
- Biaxial drive that enables 2-axis sun tracking; and
- Monitoring and control system to operate the PowerDish in remote, autonomous mode.

The concentrator, made of mirrored surface, collects and focuses the solar energy on the receiver within the Heat Drive package. That high temperature solar energy crosses the metal container at the FPSE heater head and heats a working fluid, helium, inside the FPSE generator. This is the hot side. The FPSE generator technology operates on the Stirling cycle principle whose power and efficiency are determined by a piston moving energy from a very hot source to a cold source. Work is performed as a piston shuttles back and forth moving the helium from the hot source to the cold source. A closed loop cooling system circulates a coolant fluid from the FPSE generator through a radiator, where it exchanges the collected heat to the ambient air. This establishes the cold side for the Stirling cycle. The displacer piston moving the helium from the hot side to the cold side at around 60 cycles per second causes a pressure wave to form in the helium working fluid. This pressure wave causes a second piston, called the power piston, which is connected to a linear alternator, to also move in sympathetic vibration. This second piston is associated with a magnet that is moved back-and-forth inside a stator, which in turn causes an electric current to be generated.

Figure 1 shows the PowerDish system with the concentrator, also called a reflector, as well as a close-up of the FPSE inside the Heat Drive, which is mounted at the focal point of the concentrator mirror system.

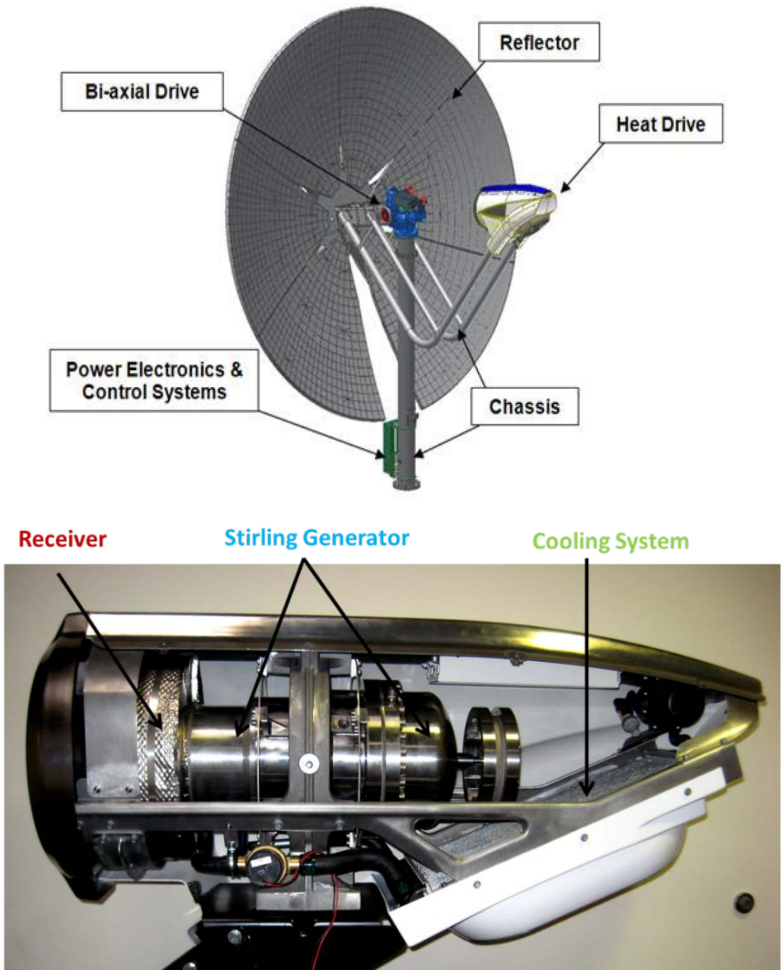

Figure 1. PowerDish components (heat drive components shown with shell removed)**.**

Figure 2 shows a cross-section of the FPSE illustrating some major internal components.

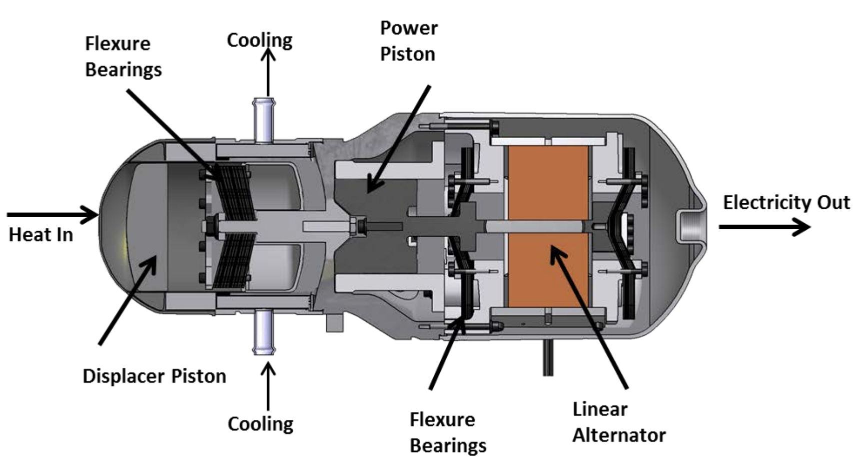

Figure 2. Free-piston Stirling generator.

For the PowerDish there are two modes of operation: “on sun” which is tracking the sun during the day; and “stowed” which is not tracking the sun and in a non-moving, safe position and condition. The PowerDish controls have been developed so that during typical operation Infinia’s proprietary software automatically sends the system “on sun” each morning and stows at sunset. If any problems are sensed in the system, i.e. a grid event, the software will stow the hardware so it does not operate. During rare circumstances, the system may be taken off sun remotely by clicking the “off” button in the software or in-person on site. As an added precaution, if the software does not take the system off sun automatically, the system can be taken off sun using an “emergency-stop” button at the site to manually disconnect the unit from the grid. The autonomous operation and automatic control was an intended cost control measure to allow remote operation oversight from either Ogden, UT or Kennewick, WA personnel via satellite internet connectivity. In the event of any operational circumstance outside of expected ranges of the measurement instrumentation on site, a fault code is triggered and immediately relayed to field engineering personnel to ascertain any need for human intervention.

2.1.2 The PowerDish CHP

The conventional PowerDish system generates heat as a byproduct of the solar thermal energy-to-electricity generation process and would normally reject most of the heat into the atmosphere through a conventional coolant-based fan and radiator sub-system. The CHP PowerDish as installed and evaluated at Fort Carson 2012 consisted of a pre-production level PowerDish generator integrated with an off-the-shelf liquid-to-liquid tube and shell heat exchanger, in order to recover the thermal energy normally wasted through the on-board radiator. Figure 3 is a picture of the heat exchanger mounted on top of the Heat Drive. The PowerDish system controls were modified to allow the cooling loop temperature, the hot side of the heat exchanger, to go up to 70EC. This modified PowerDish with the off-the-shelf heat exchanger and modified controls formed the PowerDish CHP that was used in this demonstration.

Figure 3. PowerDish CHP (heat exchanger mounted on Infinia PowerDish)**.**

2.1.3 The Building Thermal Energy Loop

To use the thermal energy available from the PowerDish CHP system, a site-specific building thermal energy loop (BTEL) and point-of-use (POU) hardware will need to be selected and designed into the overall CHP system. The liquid-to-liquid heat exchange process is utilized to capture most of the thermal energy from the engine's coolant loop and transfer the energy to the BTEL. The heated BTEL fluid is piped within an insulated piping and hose arrangement, down the post of the PowerDish to the facility. Most commonly, the systems in a CHP application include systems for extracting energy from the BTEL to heat water, air, or are stored for later use. After supplying the building systems, the BTEL fluid flows back to the PowerDish, up the post, and back into the liquid-to-liquid heat exchanger mounted above the Stirling generator.

The building systems utilized to store and transfer the BTEL heat energy can be off-the-shelf or specially designed equipment. The careful selection or design of equipment to utilize the relatively low temperature energy in the BTEL is critical to a successful installation. Typical solar components for the POU equipment in the facility include:

- Solar storage tanks, pumps and controls;
- Solar hot water heater and controls;
- Wall mounted radiators or other room exchangers for space heating;
- Programmable, multi-heat source thermostat; and
- Piping, valving, and insulation to meet local building codes.

2.2 TECHNOLOGY DEVELOPMENT

The Infinia PowerDish, in electric production only mode, has been utilized at various installations across the globe serving as both customer sites as well as Infinia corporate validation and verification facilities.

For this demonstration project, a heat exchanger was added in the engine cooling loop of an early production Infinia PowerDish. Also, the controls were modified to allow higher temperature cooling fluid to operate in the PowerDish. The resulting system was called the PowerDish CHP. Infinia's 3 kW_e PowerDish system typically rejects about 7 kW_{th} of thermal energy (at rated conditions) as a normal part of the solar-on-the-dish to AC-electric-to-the-grid conversion process. The delivery of this thermal energy to the building for thermal usefulness at point-of-use applications is a system integration effort. For the development at Fort Carson, Infinia elected to work with existing commercially available solar heated energy technologies which would be appropriate for heating, hot water production, and energy storage at the chosen facility.

Figure 4 shows heat exchanger integration and development testing (2010: left) and a demonstration for Congressman Adam Smith, October 2011, at Infinia's Kennewick facility (right).

Figure 4. Heat exchanger integration and testing.

Additional information regarding specific programming and development changes for the Power Dish CHP is available in the Final Report.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The FPSE as a solar energy conversion source for both electrical and thermal energy allows both heat and power to be generated at conversion efficiencies projected as high as the 70% range. This CHP technology integrates solar electric production and hot water production into a single system versus the need for two independent solar systems. The PowerDish CHP technology will help reduce DoD's energy burden and carbon footprint through on site production of electricity and hot water with a single system utilizing a free, non-GHG producing fuel source, the sun, at either domestic or deployed installations. Potential deployment to FOBs can provide even greater gain as standard fuel transport and logistics expenses are offset through the use of the PowerDish CHP system as a supplemental energy source. The disadvantage for the PowerDish CHP system at FOBs is the large profile, heavy system, and need for substantial foundation support to offset wind loading.

As solar resources vary with the seasons, climate, and weather, the ability of this technology to be a primary electrical and thermal energy source is not always reliable. But as a supplemental and at times primary source, it is entirely feasible especially in the global environments of greatest Direct Normal Irradiance (DNI) potential (especially 5.5 kW hours (kWh)/square meter (m^2)/day and higher as shown in continental U.S. map in Figure 5). The PowerDish as being deployed in its 2014 model, PowerDish V, will be competitive with PV produced electricity ($/megawatt hour (mWh)) in places around the world where DNI is 5.5 kWh/m^2/day or higher. The installed PowerDish system usually costs more ($/watt (W) than PV but produces 15% -

50% more mWh/year (depending on the type of installation). As a result, on a $/mWh basis the PowerDish is competitive with PV. Consequently, in those locations, the PowerDish CHP system is expected to be more cost effective than a PV system for electricity and a solar thermal system for hot water.

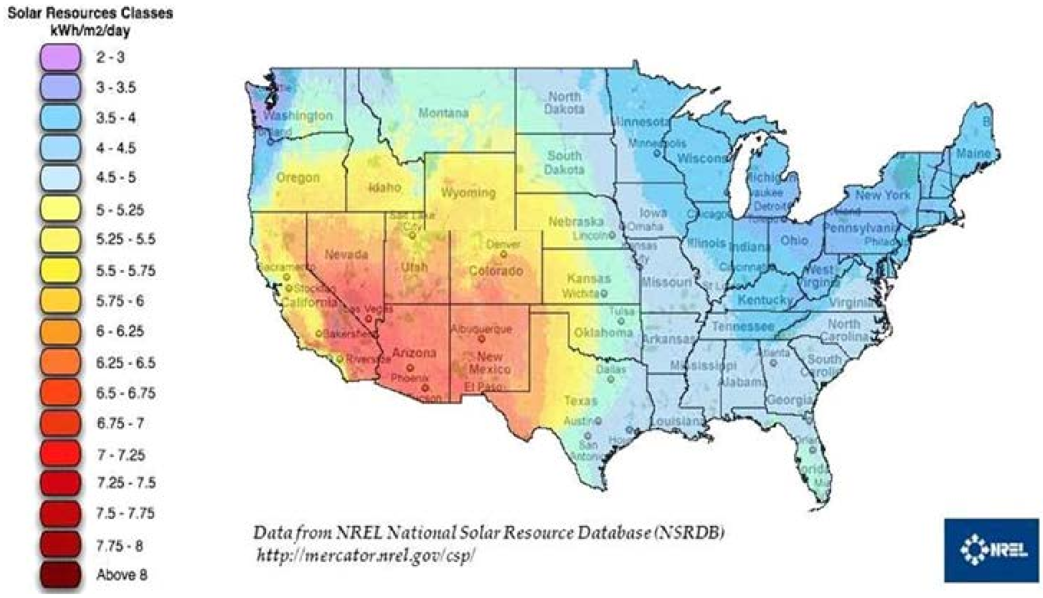

Figure 5. Domestic solar resources.
(National Renewable Energy Laboratory [NREL] database)

3.0 PERFORMANCE OBJECTIVES AND OUTCOMES

The following Table 1 is the Performance Objectives Results Summary showing the results of the Fort Carson demonstration.

Table 1. Performance objectives results summary.

Performance Objective	Domestic Power Success Criteria	Fort Carson Demonstration Results	Comments
Monitor Estimated Facility Energy Usage "Facility Energy Consumption"	Comparable to Estimated Facility Baseline: 16,800 kWh/year electric	7887 kWh (46.9% of estimated baseline)	Electric and propane meters were installed. Fewer occupants in building than expected. Less delivered CHP energy to space heating during the winter months caused more propane to be used than expected.
	Comparable to Estimated Facility Baseline: 1200 gallons/year liquid propane (110.55 million British thermal units [BTU])	1182.6 gallons (31,931 kWh) of propane consumed + 76.5 gallons equivalent of thermal energy from CHP = 1259 gallons propane equivalent consumption (116.0 million BTU) (104.9% of propane consumption baseline)	
Maximize Renewable Energy Usage "PowerDish Energy Supplied"	30% Compared to Baseline: 5040 kWh/year electric	4315 kWh electric (kWh_e) produced 4238 kWh_e delivered (54% of actual consumption) (25% of estimated baseline) (less 167 kWh from heat loop) Pump energy consumption – CHP implementation	The PowerDish CHP provided 86% of the expected electric generation to meet success criteria. Outages and Infinia imposed output restrictions caused the lower output. The CHP system provided 69% of the thermal energy expected to be PRODUCED but only 13% of the expected DELIVERED energy. Less delivered CHP energy to the building had multiple causes including: • PowerDish CHP outages; • Infinia imposed temperature reduction and output restriction; • Underperforming CHP heat exchanger; • Suboptimal POU operating design for first winter months; and • A facility that required almost no thermal energy for 6 of the 12 months. In hindsight, the success criteria were incorrectly set considering this last point: 4000 kWh_{th} delivered may have been more appropriate target.
	~50% Compared to Baseline: 16,000 kWh/year (55 million BTU) thermal potential	11,110 kWh thermal (kWh_{th}) produced (37.9 million BTU) 2082 kWh_{th} delivered (7.11 million BTU) (6.1% of total building thermal consumption) (6.4% of estimated baseline)	

Table 1. Performance objectives results summary (continued)**.**

Performance Objective	Domestic Power Success Criteria	Ft. Carson Demonstration Results	Comments
Maximize Savings for System Economics "Fuel and Electricity Reduction Savings"	20+ years with maintenance	Generator failure during the demonstration resulted in revisions to the demonstration PowerDish CHP controls and design improvements for subsequent PowerDish generators when operating in CHP mode (higher cooling loop temperature).	CHP weakness exposed in PowerDish design that was used. Improved durability expected from production systems with design changes eliminating the condition that contributed to low generator output and higher maintenance.
	~50% Fuel Savings: $1100/year potential propane savings	$145 savings (rate $1.90/gallon)	As described above, low DELIVERED thermal energy caused the lower savings. Hindsight shows that for this building, with thermal requirements only in about 6 of 12 months, the success criteria was about 4X too high.
	~30% Electricity Savings: $252/year savings in electricity	$212 savings ($0.05 rate) – $8 for the building heat loop pump energy = $204 saving net	Lower electric production, described above, caused the lower savings.
Minimize Direct Greenhouse Gas Emissions "Fuel Consumption Offset"	~50% Compared to Baseline: 600 gallons/year propane reduction potential	96.4 gallon reduction in propane consumption (including propane burner inefficiencies) from the delivered thermal energy to the building: 2082 kWh. Also, 4238 kWh_e off-set carbon dioxide (CO_2) emissions from CSU generation.	As described above, low DELIVERED thermal energy caused the lower propane savings. Hindsight shows that for this building, with thermal requirements only in about 6 of 12 months, the success criteria was about 4X too high.
	~50% Compared to Baseline: 7000 pounds/year CO_2 potential reduction	1233 pounds of CO_2 emissions were reduced from the propane reduction from the thermal energy delivered to the building. Additionally, 7459 pounds of CO_2 were reduced from the electric offset. 8692 pounds CO_2 were reduced from the CHP demonstration.	See comment above. Lower CO_2 is directly related to lower propane savings.
Monitor Facility Metering	Meter building for electricity, thermal, and fuel consumption: comparable to "Estimated Facility Energy Usage" values	Facility electricity, and thermal metering (flow and temperature sensors) was installed and monitored remotely via satellite internet and 24 hour data logging. Propane meter log was only read onsite.	Met criteria. Some data "dropouts" did occur from grid outages, internet outages, and sensor failures.

Table 1. Performance objectives results summary (continued)**.**

Performance Objective	Domestic Power Success Criteria	Fort Carson Demonstration Results	Comments
Monitor System Maintenance	Mirror cleaning - once every 2 weeks. No other maintenance expected in the first year. Replacement expected for the pump, fan, coolant after 7 years	Mirror cleaning at 6 to 8 week intervals (lower DNI from soiling was acceptable in reduced power mode); Slew Cone checks/ replacement followed same frequency (PowerDish design changes have eliminated slew cone maintenance); PowerDish generator replacements occurred due to generator failure; design changes were made to in-building space heating applications	Monitoring (remotely) was done as expected. Long-term maintenance would not be an issue for many years. The mirror cleaning was reduced because the resulting lower output (more margin at high DNI conditions) supported the generator protection scheme Infinia put in place.
Monitor System Integration	No problems expected with other systems	Heat delivery system: 1) Needed better match of generator/building loop heat exchanger with the low CHP temperatures; 2) Needed careful selection considering the low CHP temperature for "off-the-shelf" solar heating components in the building thermal delivery systems; and 3) The revised design, which had heat loop liquid going to end-uses FIRST and then to thermal storage tank LAST, made better use of the CHP system to offset fuels for end-use application (space & water heating).	Lessons learned for design and operation of the building thermal loop and POU applications. Systems integration was one of several contributing factors for lower thermal delivered energy to the building.

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4.0 SITE/FACILITY DESCRIPTION

4.1 SITE/FACILITY LOCATION, OPERATIONS, AND CONDITIONS

Fort Carson Directorate of Public Works (DPW), in consultation with Infinia personnel, selected the Administration Building (#9246) based on the desired criteria for the solar CHP application. Building #9246 (Figure 6) at Fort Carson is a 1320 square foot (ft^2), single story, mobile office unit. The number of building occupants can vary year round between four and six DPW staff. During the entire demonstration period two DPW personnel staffed the building.

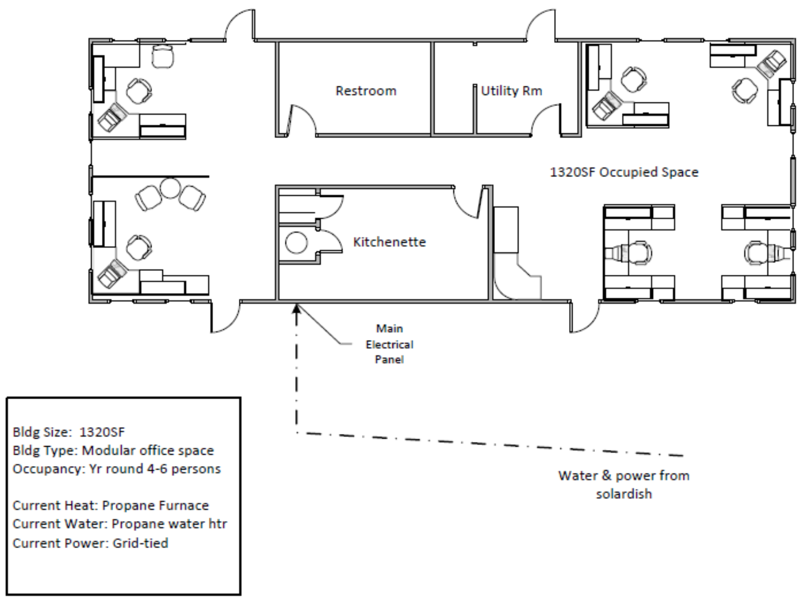

Figure 6. Fort Carson Building #9246 layout.

Site maps are depicted below in Figure 7 and Figure 8. Building #9246 is located in the southern portion of the Fort Carson Army base along Butts Road. The site is managed year-round, but is not heavily trafficked, so hindering effects to the demonstration project's installation and/or performance data monitoring were not an issue.

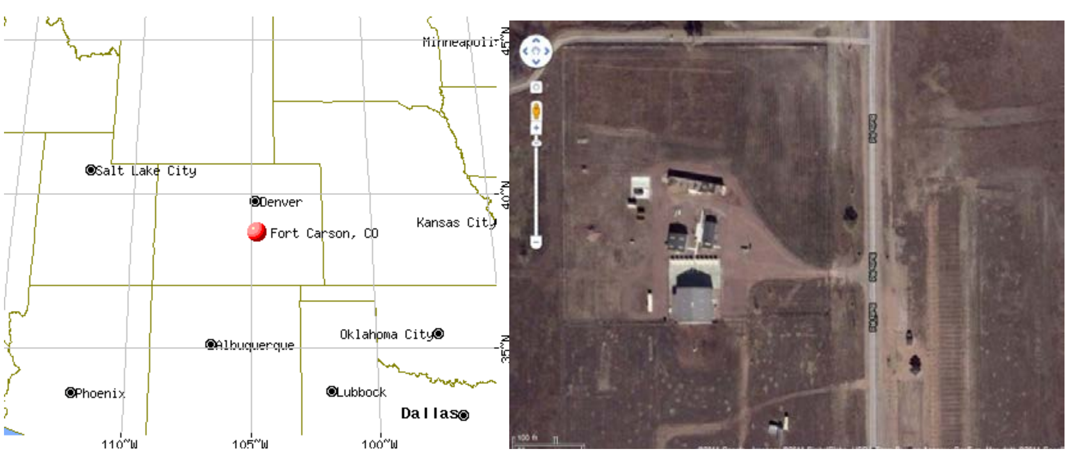

Figure 7. Fort Carson site maps (aerial photo prior to installation)**.**

The Infinia PowerDish was sited approximately 200-ft to the front of Building #9248, which is adjacent to the Hazardous Waste Storage Facility Administration Building #9246. The balance of plant components are all situated within the Administration Building. The site plan and building site depiction, Figure 8, shows the installation locations.

The placement of the dish in the grassy region in front of Building #9248 was determined by several restricting infrastructures and site features including: existing underground piping, a 50-ft Poplar tree just inside the facility's fence line, and the integration of supporting performance monitoring structures. Approximately 250-ft of underground piping extend towards Butts Road from Building #9248. The piping served as a boundary that could not be trespassed.

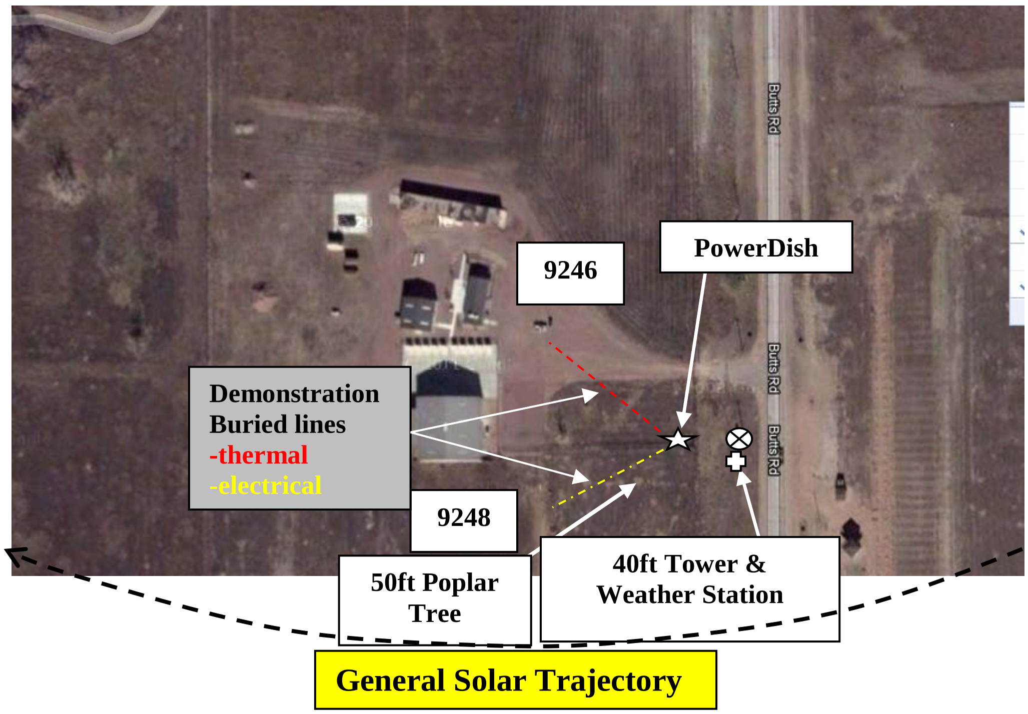

Figure 8. Building site power dish deployment depiction.

4.2 SITE/FACILITY IMPLEMENTATION CRITERIA

Administration Building #9246 and grounds were selected as an applicable demonstration site primarily due to the facility size, estimated energy use, and occupancy level. The facility was expected to consume much more than 5000 kWh/year and much more than 55,000 million BTU/year for thermal energy use for water and space heating. The Fort Carson Facility has an appropriate geographical location for higher DNI profile (projected in the 6-7 kWh/m^2/day range) which is beneficial to solar energy systems although its location near the base of Cheyenne Mountain was shown to create a transient cloud effect which reduced output.

The Hazardous Waste Site has flat terrain with a good southern exposure (except for a poplar tree in late winter afternoons) and enough surrounding square footage for the necessary weather instrumentation. The site was determined able to accept buried communications, fluid and

electrical conduits between the instrumentation and to the appropriate building locations without creating interruption to the other buried services already present.

During the facility selection process and at the start of the demonstration the building occupancy was thought to be between four and six daily occupants which was appropriate for an energy consumption profile for a building of this size. But due to base needs some of those personnel were relocated the other facilities during late 2011 and early 2012 resulting in a lower than expected occupancy level (two and three personnel). This lower occupancy likely had effects on the actual energy consumption versus the expectations.

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5.0 TEST DESIGN AND ISSUE RESOLUTION

5.1 INITIAL CONCEPTUAL TEST DESIGN

The ESTCP Solar CHP Demonstration Project objective was to demonstrate that the Infinia PowerDish (electric only) could provide both electric and thermal energy when developed as a CHP device.

The demonstration established estimated output from the PowerDish CHP that would be available for use in end-use application, within Building #9246. The estimates were based on:

- The PowerDish model that was modified;
- The heat exchanger that was selected for the interface between the PowerDish cooling loop and the building thermal energy loop; and
- The location of the installation so that DNI and other weather data could be accessed, and its implication on the electric and thermal output of the engine.

The demonstration also established estimates of the amount of electric and thermal energy demand (from propane) for Building #9246 confirming that it was sufficiently large enough that the energy produced by the PowerDish CHP would be consumed. It was recognized from the start that while the annual thermal energy demand was sufficiently large enough, the use was not uniform throughout the year. During the late spring, summer, and early fall there would be very little need for thermal energy, e.g., no space heating requirement and very little water heating for the Building. As a result, during a significant period of the year almost no thermal energy (although available) would be transferred to the building.

A suite of sensors, meters, and monitoring/communications system were installed at appropriate points throughout the installation to monitor, measure, record, and report the energy and energy related parameters that enabled the building use and the PowerDish CHP production of electricity and thermal energy flows to be captured.

After the year-long demonstration period, the data collected on the Building energy consumption and the PowerDish CHP production could be evaluated and compared to the estimates so that judgments could be made about the effectiveness of the CHP system. Further, the analysis of the effectiveness of this demonstration for Building #9246 could provide insights into how:

- To make improvements to the PowerDish CHP system, the heat exchanger system, and the selection of appropriate end-use systems, to deliver more useable energy to a DoD facility; and
- To better understand the DoD facilities that should be selected for this type of solar CHP application.

5.2 BASELINE CHARACTERIZATION

The baseline weather conditions were estimated by using typical meteorological year (TMY) data from NREL's Solar Prospector, which takes the most typical measured weather conditions for Fort Carson for a period of over 8 years. The PowerDish CHP was estimated to produce 5040 kWh_e and 16,000 kWh_{th} energy annually.

The baseline electrical energy consumption for the building at Fort Carson was estimated based on the square footage of a Building #9246, and the expected number of building occupants. The electrical baseline estimate for the building was 1400 kWh/month or 16,800 kWh/year. The propane baseline was estimated to be around 1200 gallons/year. The building is mainly utilized as an office building with almost no hot water use in the summer.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The physical layout of the PowerDish CHP system relative to Building #9246 and the electrical interconnection is shown in Figure 9. A direct electrical production interface with the Fort Carson power grid was established via a buried, 150 ft run of grounded, 3 conductor (for 3-phase electricity), 10 American wire gauge (AWG) cable, running from the point of power metering at the outdoor, weather proof containment disconnect switch box located near the dish.

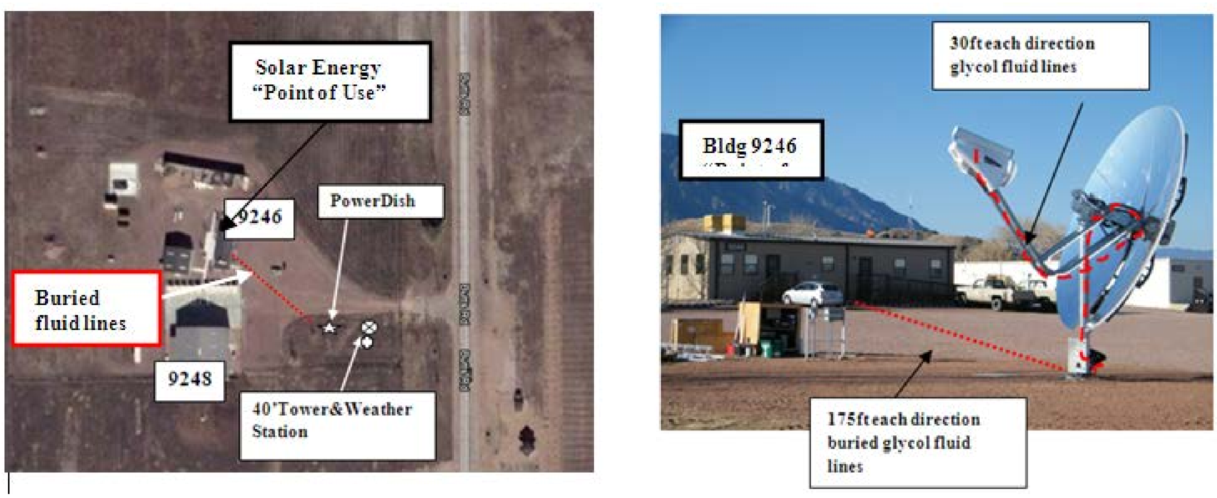

Figure 9. PowerDish CHP installation: aerial and ground level views.

A conceptual pictorial graphic is shown in Figure 10 depicting major BTEL components and sensors in the system as installed in the revised design layout. Additional information is available in the Final Report.

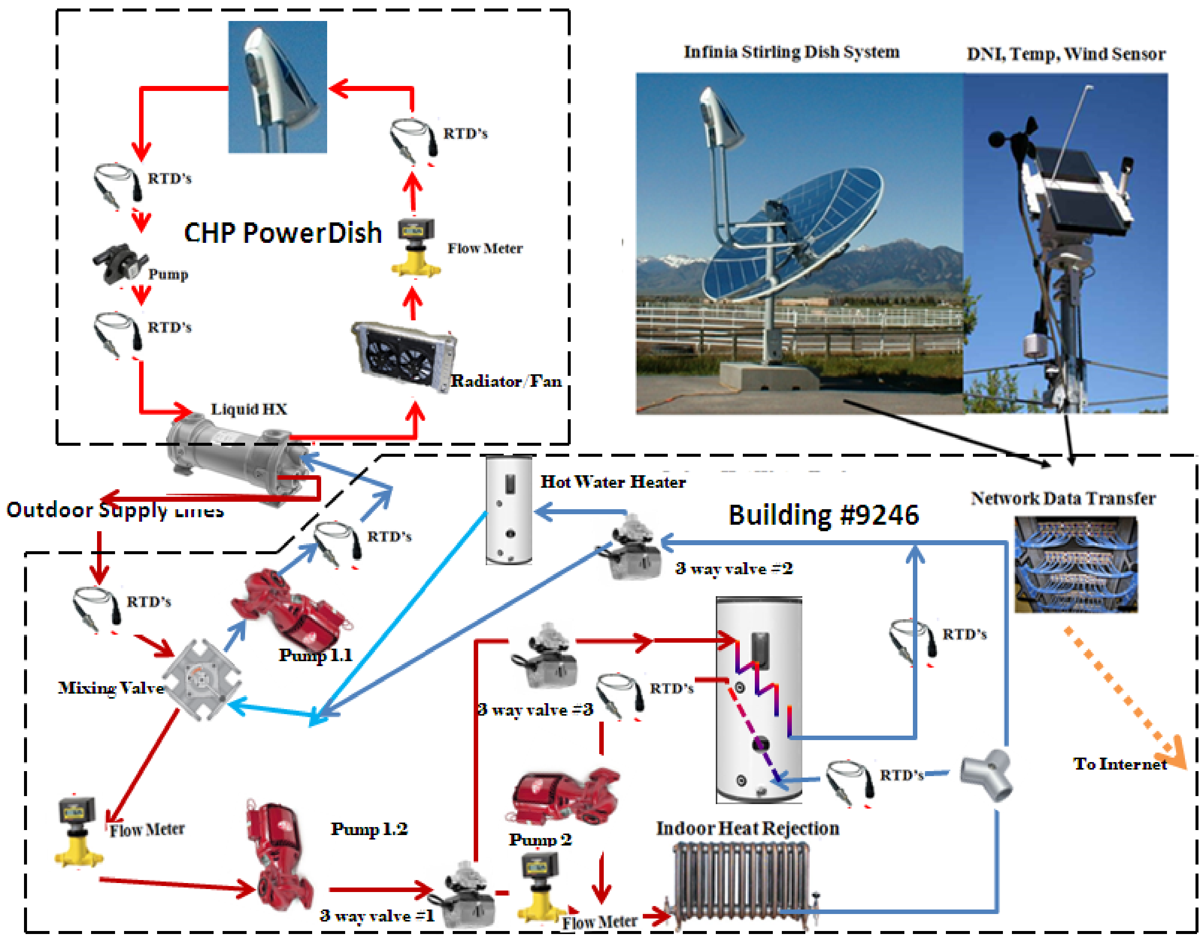

Figure 10. Solar PowerDish CHP REVISED design pictorial graphic.

The initial building heat loop design took the heat from the engine cooling loop (closed loop system) of the PowerDish, through a heat exchanger and into the building heat loop (a closed loop design). The heated fluid then passed through a solar storage tank and then a return loop back to the heat exchanger at the engine. Hot water loops from the solar storage tank took heat to the radiators for space heating and to the Hot Water tank for hot water heating.

Following the poor solar heat utilization in Building #9246 during the initial period of January–April 2012, the building heat loop design was revised (redesigned) to have the heat from the heat exchanger at the engine flow directly to the building radiators first, and then flow to the storage tank. This redesign significantly improved the amount of heat that was delivered to the space heating within building and directly reduced the amount of propane used through the work day to keep the temperature inside the building at the desired set-point.

5.4 OPERATIONAL TESTING

The demonstration period began January 17, 2012, following pre-shipment testing, commissioning, and an early engine failure and ended December 31, 2012. The performance data was monitored remotely via a network satellite system on a daily basis to ensure proper system

function, correct data acquisition transfer, and to spot problems quickly so they could be resolved. The daily performance data was compared against system models to confirm the performance objectives were in line with predictions or to take corrective actions. The sensor outputs were also observed to ensure the sensors were functioning properly and providing accurate performance measurement data during operation. The daily data was logged and analyzed for engine performance, production output, energy delivered to the grid, building system function and performance, as well as building energy consumption levels.

5.5 SAMPLING PROTOCOL

The installation and integration of Infinia's CHP PowerDish with Building #9246 required multiple power, temperature and flow sensing devices in order to monitor performance and capture the necessary data for assessing functionality. All of the data except for propane consumption was captured on a 24/7 basis at a 6 second sample rate. The raw data stream from each of these meters and probes (except propane) was sent to Labview data acquisition system where it was post processed based on each individual instrument's calibration information. The processed data was then recorded at the given sample rate and saved into daily data log files. These daily files were stored on the installation site computer and downloaded daily to a resident computer at the Infinia Kennewick location for analysis. Propane consumption data was also logged on a 24/7 basis through a Hobo-Meter system which required that manual recovery, by either Infinia of contracted personnel, be conducted on site at regular intervals.

The PowerDish electrical production data was gathered through the onboard measurement equipment and control software in conjunction with an installation weather station and anemometer tower through standard Infinia procedures and methodologies. With the weather station and anemometer tower inputs, the proprietary software assessed the units electrical production relative to the changing daily environmental conditions. This data was then charted on a daily basis versus a standard 2.7 kW_e predicted production level as an assessment of performance and function.

Using the data, the electrical power production over time and the thermal energy produced at the engine and made available for building heat and hot water was calculated. Electrical energy consumption was measured and logged through the same labview system as previously described which allowed consumption over time assessments to be made easily through the use of excel macro based programming. Propane consumption required manual data analysis that resulted in daily consumption levels which were then compiled into cumulative summaries.

A full listing of the sensors, their location, and data captured can be found in the Final Report.

6.0 PERFORMANCE ASSESSMENT

During the demonstration, energy consumption within building #9246 was monitored on a 24/7 basis. The energy consumption meters, both electric and gas, were added at the time of the project installation because the building did not have its own electrical or propane metering systems. Therefore, historical electrical consumption data and propane use data for Building #9246 was unavailable. Baseline estimates were made based on occupancy and estimates from "bulk" propane deliveries and electric bills which were for a larger group of buildings. The result is that the comparisons for energy savings purposes can only be extrapolated from the data gathered during earlier periods of the project year or from the estimated values utilized in the proposal and demonstration plans. Those estimated values for the initial proposal, before the project start, consisted of:

1. Predicted facility electricity consumption of 16,800 kWh/year and
2. The best estimated guess of 1200 gallons of yearly propane consumption or 32,400 kWh/year equivalent (using 27 kWh/gallons as a conversion factor).

Because the electricity provided to the grid went into the general electric grid and did not directly offset the electric consumption, the electric consumption of the building is the direct measurement of the meter installed at the building. However, the thermal energy delivered to the building loop and used within the building offset the use of propane for space and water heating. Therefore, the total thermal energy used by the building was the thermal energy provided by the CHP system plus the measured Propane use. Table 2 compares these predictions to the actual measured consumption values during the demonstration period.

Table 2. Building #9246 energy measured consumption versus project estimates.

Energy Type	Measured Consumption (kWh)	Actual Building Consumption (kWh)	Initial Estimated Consumption (kWh)
Electric (kWh)	7887	7887	16,800
Total Propane Equivalent		34,013 (1260 gallons)	
Propane (kWh)	31,931 (1182.6 gallons)		32,400 (1200 gallons)
Total Equivalent from CHP (kWh)	2082 (77.1 gallons equivalent)		
Total Energy		**41,900**	**49,200**

Table 3 presents the monthly electric consumption (measured at the breaker panel inside the building) and PowerDish delivered electricity (measured just before the grid interconnection). During the periods of data acquisition outages noted in the Table, the building consumption and PowerDish production were estimated based on surrounding monthly data and the PowerDish inverter production data. There is a small energy usage that is included in the building consumption numbers that are a result of implementing the CHP application. That small energy use is from two motors in the building heat loop and one motor in the radiator loop that move the fluid throughout the heat loop. These motors were not metered. They did run in a full-on or full-

off mode at about 35 Watt/motor when running. The best estimate of their contribution to the building electric consumption is 167 kWh over entire demonstration period: about 2% of the building consumption. The consumption numbers have not been reduced for this motor usage.

Table 3. Monthly electrical consumption and production.

Time Period	Building Electric Energy Consumption (kWh_e)	CHP Delivered Electric Energy (kWh_e)	Percent Delivered/ Consumption
January (17-31)	338.9	128.2	37.8
February	729.6	281.4	38.6
March	761.1	450.8	59.2
April	655.9	470.5	71.7
May	646.7	507.5	78.5
June	640.2	444.1	69.4
July (3 days estimated)	615.3	315.6	51.1
August (6 days estimated)	539.6	231.6	42.9
September (26 days estimated)	470.3	303.4	64.5
October (9 days estimated)	685.0	418.4	61.1
November	723.8	391.1	54.0
December	1080.0	296.9	27.5
Electricity during demo period January 17 thru December 31, 2013	7886.6	4238.4	53.7

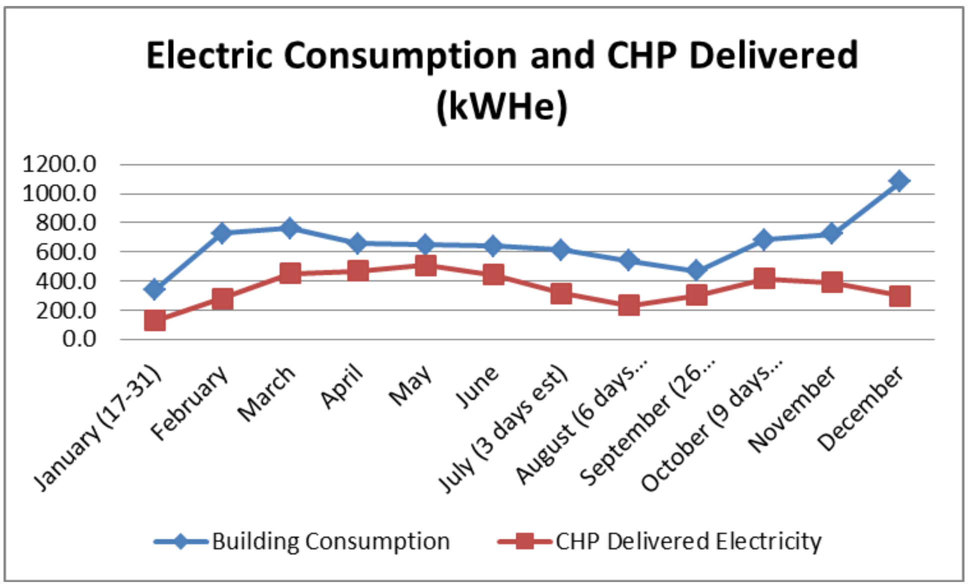

Figure 11. Monthly electrical consumption and production.

The building actual electrical consumption figures are considerably lower as compared to the initial estimates and this can only be partially explained. When the project started and the predicted usages made, the building living space was occupied by over five people but at the time of the installation and over the full year demonstration period the occupant level dropped to two people. Also as part of the project scope, during the November 2011 installation a

programmable thermostat was installed and was set for typical daytime needs as well as energy conserving, night time set-backs. The system was configured to not allow the building occupants to change the furnace operational controls, thereby ensuring a consistent demonstration period operation. The effects of this thermostat control scheme are visible for both electric (fans) and propane consumption when comparing the month-to-month consumptions versus the December 2012 data. On approximately December 10, 2012, Fort Carson personnel had the project thermostat removed and replaced with a manual control device, for fear of pipe freeze during the winter period.

Table 4. Monthly thermal energy usage (propane and from CHP).

Time Period	Measured Propane Usage (kWh_{th})	Measured Propane Usage (gallons)	Thermal Energy Delivered to Building Heat Loop (kWh_{th})	Total Building Thermal Energy Consumption (kWh_{th})	Total Building Thermal Energy Consumption (kWh_{th})
January (17-31)	2820.2	104.45	120.9	2941.1	108.93
February	7089.0	262.55	234.7	7323.7	271.25
March	2513.1	93.08	296.7	2809.8	104.07
April	1372.3	50.82	259.0	1631.3	60.42
May	587.5	21.76	225.0	812.5	30.09
June	274.5	10.16	151.1	425.5	15.76
July	248.5	9.20	115.3	363.8	13.47
August (15 days estimated)	323.4	11.98	23.8	347.1	12.86
September (30 days estimated)	1479.0	54.78	0.0	1479.0	54.78
October (4 days estimated)	2926.6	108.39	94.8	3021.3	111.90
November	4208.0	155.85	325.2	4533.2	167.90
December	8088.9	299.59	235.8	8324.7	308.32
Electricity during demo period January 17 thru December 31 2013	31930.7	1182.6	2082.3	34013.1	1259.7

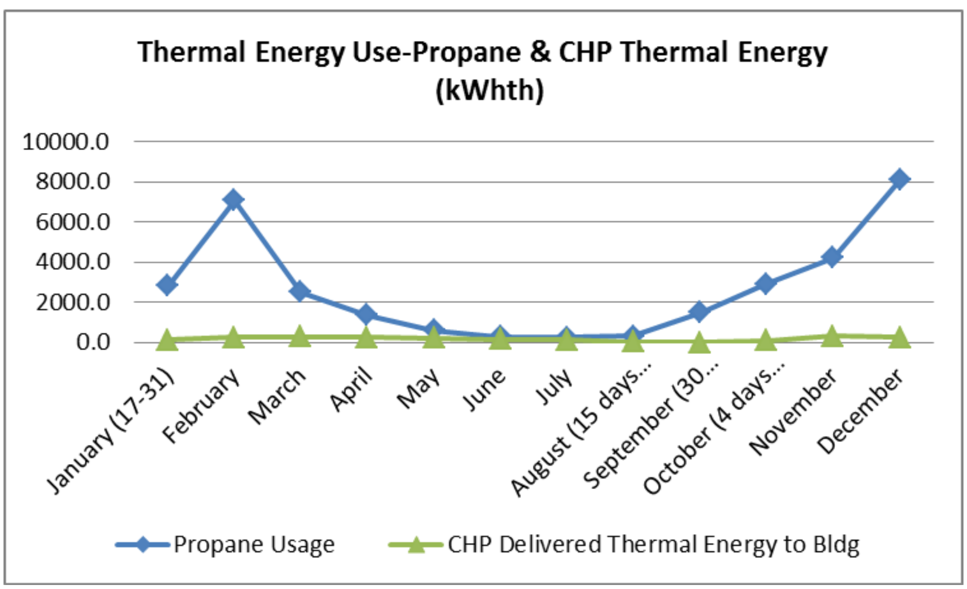

Figure 12. Monthly building thermal energy consumption and CHP delivery.

The propane figures align very well and will not change significantly if the propane data capture system had been operational during the full August through October period, as this is still a relatively low heating need period and only the hot water system would have been calling for propane energy.

In regards to renewable targets, it was stated that the PowerDish CHP target for the demonstration was to produce 30% of the electricity compared to the baseline estimate for the building consumption and to provide thermal energy to offset 50% of the estimate for the building consumption of thermal energy from propane.

Table 5 compares the PowerDish CHP energy delivered to the initial estimated consumption.

Table 5. Delivered thermal energy as a percentage of initial estimated building consumption.

Power Type	CHP Delivered Energy (kWh)	Initial Estimated Consumption (kWh)	Percent of Delivered Energy to Estimated Consumption
Electric (kWh)	4238	16,800	25.2%
Thermal (kWh)	2082	32,400 (1200 gallons)	6.4%
Total Energy	**6320**	**49,200**	**12.8%**

As a point of reference, Table 6 shows the PowerDish CHP energy delivered compared to the actual building consumption.

Table 6. Delivered thermal energy as a percentage of actual building consumption.

Power Type	CHP Delivered Energy (kWh)	Actual Building Consumption (kWh)	Percent of Delivered Energy to Estimated Consumption
Electric (kWh)	4238	7887	53.7%
Propane (kWh/gallon)		34,013 (1260 gallons)	
CHP Thermal (kWh/gallon)	2082	2082 (77.1 gallons equivalent)	
Propane Equivalent Thermal (kWh/gallon)			4.6%
Total Energy	**6320**	**43,982**	**14.4%**

Electric output was lower than anticipated as a result of two key factors, discussed below. Additional detail on the troubleshooting of these issues can be found in the Final Report.

1. PowerDish forced outages: 19 days in total with limited or no PowerDish operation due to PowerDish outage or control system forced outage; and
2. The controlled reduction of energy output that was implemented in order to maintain autonomous operation without generating system faults and potential PowerDish generator damage (>10% reduction over entire period).

The thermal energy performance objective was for ~50% production of the baseline estimate of 33,789 kWh (~1200 gallon of propane use/year); a target of 16,000 kWh. The baseline estimate was for the estimated amount of propane that was being consumed annually to provide the space heating and water heating requirements of Building #9246. So, the amount of thermal energy expressed in the performance objective is for a percentage of energy used in the building for space and water heating. Thus, the performance objective target should be for the amount of thermal energy delivered to the building heat loop system for building application use. Table 6 above provides the actual thermal energy used by the building heat loop from the PowerDish CHP. This value, 2082 kWh, is only 6.4% of the baseline estimated consumption of 1200 gallons or 32,400 kWh. This is well below the performance objective target of 50% of baseline or about 16,000 kWh. The baseline of 16,000 kWh is more closely related to the amount of thermal energy actually produced in the PowerDish CHP system measured in the PowerDish cooling loop (at the engine heat exchanger): a value of 11,110 kWh_{th}. But, it is clear (in hindsight) that the performance objective target was incorrect for delivered thermal energy.

6.1 MAINTENANCE OBJECTIVES

The demonstration PowerDish CHP was a modified pre-production PowerDish system. The increased PowerDish cooling loop temperature was a potential risk of generator damage for the PowerDish III (and earlier) models. Due to design changes, subsequent models do not have that same risk of generator damage when in CHP mode of operation. The electric-only version of the upgraded PowerDish models are expected to operate in excess of 25 years with scheduled maintenance. The CHP version of the PowerDish 5 will be expected to also have a greater than 25 year life with scheduled maintenance. The PowerDish III model systems are no longer produced and are no longer available.

Because of the long periods between scheduled maintenance, an annual operations and maintenance (O&M) reserve is sometimes used to put some financial reserves back to pay for the scheduled maintenance that occurs much later in time. A suggested reserve for the scheduled maintenance is about $30/kW/year or about $90/year. The periodic cost of cleaning the mirrors is in addition to this reserve for scheduled maintenance. The frequency of mirror cleaning is solely dependent on the local site characteristics: the environmental conditions (dust, etc.); the cost of labor and water; the value of the kWh produced and fuel costs avoided. Improved durability is expected in the current and future PowerDish models versus the model used in the CHP demonstration.

6.2 GHG OBJECTIVES

The CSU generation is mostly coal and natural gas in large steam power plants. They do not report on their website their CO_2 emission rate, but from Energy Information Agency (EIA) information, www.eia.gov, for the Colorado state profile, Colorado electric utilities produce CO_2 at a rate of 1760 pounds CO_2/mWh (1.76 pounds/kWh). The EIA also provide the CO_2 emission factors by fuel type:

- Propane produces about 5.8 kilograms/gallon (12.79 pounds/gallon) of CO_2 per gallon burned; and

- Diesel fuel produces about 10.2 kilograms/gallon (22.49 pounds/gallon) of CO_2 per gallon burned.

The demonstration achieved 4238 kWh_e to the grid and avoided the production of about 7459 pounds of CO_2 from electricity (1.76 pounds/kWh *4238 kWh). Further, the 2082 kWh_{th} delivered to the building heat loop off-set 96.4 gallons of propane (when considering the conversion efficiency of the end-use systems). These saved gallons of propane reduced the CO_2 emissions by 1233 pounds (96.4*12.79). The demonstration also reduced the CO_2 emissions by 8692 pounds; exceeding the stated performance objective of 7000 pounds CO_2 reduction.

7.0 COST ASSESSMENT

This section provides the calculated life cycle operational costs for the PowerDish CHP technology. It is not very useful to describe the costs for the non-commercial, modified PowerDish system that was used in the demonstration and which is no longer available. Rather, the cost assessment will focus on a PowerDish 5 based CHP system and the competing choices faced by a customer considering what to use for a combined electricity and thermal energy application. The PowerDish III-based CHP system used in the demonstration was a 3.0 kW rated system that was downgraded by the control system operation first to 2.7 kW and then lower. The PowerDish 5 system considered in this Cost Assessment Section is a 7.5 kW rated system.

7.1 COST MODEL

Table 7 summarizes the key cost elements for an installation of the PowerDish CHP, identifies some of the data elements tracked during the demonstration, and provides estimates for a next generation PowerDish CHP implementation.

Table 7. Important costs for implementing the PowerDish CHP.

Cost Element	Data Tracked During the Demonstration	Estimated Costs for Future Implementation
Hardware capital costs	Component costs for the PowerDish CHP, space and water heating, and all other hardware components in the demonstration	$15000 (PowerDish 5 with heat exchanger) + $10,000 (in-building application hardware) = $25,000 CHP system hardware
Installation costs	Labor and material required to install	$10,000 (installation of PowerDish) + $10,000 (installation of in-building systems) = $20,000 Installation Costs
Consumables	Estimates based on rate of consumable use during the demonstration	Water: 60 gallons/year
Facility operational costs: • **Electric cost** • **Energy cost for thermal loads**	• Electricity cost and quantity that can be avoided • Cost and quantity of fuel for space and water heating that can be avoided	Electric: 20,044 kWh/year @$0.11/kWh (average) = $2205/year Thermal: 68.4 million BTU/year use @85% gas to thermal use conversion @ $6.50/MMBTU* = $523/year
Maintenance	• Frequency of required maintenance • Labor and material per maintenance action	Incremental above existing systems: $225/year ($30 per KW installed) PLUS the periodic cost of mirror cleaning
Estimated salvage value	Estimate of the value of equipment at the end of its life cycle	10% of initial cost
Hardware lifetime	Estimate based on components degradation during demonstration	20 year
Operator training	Estimate of training costs	Incremental: minimal

*MMBTU = million British thermal units

7.2 COST DRIVERS

7.2.1 Hardware Capital Costs

The PowerDish CHP system (PowerDish 5 based system) will be the largest single component cost for the installation. The PowerDish 5 CHP system will benefit from volume production of the system and lower cost per unit of output is anticipated. However, the selection of space heating, water heating, and heat storage component choices will significantly affect the cost and benefits of an implementation. The size of the thermal storage system and its integration into the thermal system are important considerations for the overall performance and economics of the installation.

7.2.2 Installation Costs

The foundation for the PowerDish CHP and the electric interconnection costs are important considerations, but the space heating, water heating, and storage tank components and their interconnectedness are the dominant costs for the CHP installation.

7.2.3 Consumables

The only consumable for the PowerDish CHP system is small amount of water (7-10 gallons of water/washing) that is used to clean the mirrors of the concentrator dish periodically. While there is no requirement for cleaning the concentrator dish for the system to operate, more output (electric and thermal heat) will be available with clean mirrors. The timing of the mirror cleaning is a function of the labor and water costs for cleaning and the avoided electric and fuel rates at the site.

7.2.4 Facility Operational Costs

Electric Cost and Quantity Avoided: The PowerDish CHP is a concentrator solar system. As such, its performance is greatly affected by the quantity of DNI available at a site. DNI is measured instantaneously as power (W/m^2) or is expressed over time as energy (kWh/m^2/time period). For example, the electricity (and thermal energy provided) for a site in the U.S. southwest (7-8 kWh/m^2/day average) can be two to four times the output from a site in parts of the northeast (2-3 kWh/m^2/day). But the value of the thermal heat can be more valuable for a colder climate like the northeast site. Sites that are away from the coasts and at somewhat higher altitude will perform better (often very much better) than a site at the ocean. But areas that have a very high electric rate and/or very high thermal fuel cost can provide opportunities for the PowerDish CHP in areas that may be lower DNI.

7.2.5 Maintenance

The PowerDish is a low maintenance system featuring a generator that does not need upkeep for the life of the system, and long maintenance cycles for the other components. Because of the long periods between scheduled maintenance, an annual O&M reserve is sometimes used to pay for the scheduled maintenance that occurs much later in time. A suggested reserve for the scheduled maintenance of PowerDish 5 is about $30/kW/year or about $225/year (although a lower O&M reserve is anticipated).

The PowerDish CHP system integrated with a building thermal energy system will require some annual maintenance to confirm that the systems are not leaking, and are functioning properly. These CHP systems will need maintenance similar to the heating and cooling systems they are supporting or replacing. In these economic analyses, it is assumed that the facility has some maintenance personnel covering the facility. Only the incremental costs for the PowerDish CHP routine maintenance (mirror washing) are considered in this study.

7.2.6 Estimated Salvage Value

This varies substantially with the duty cycle of the CHP application. Generally, the PowerDish (electric only) system is estimated to have a 10% salvage value after its 25 year life cycle.

7.2.7 Hardware Lifetime

The PowerDish electric only system has a lifetime of 25 year or greater. The system life estimates have been made from engineering analysis and from field experience of PowerDish units (electric-only) that have been installed. When incorporated into a CHP system, the PowerDish CHP may have a 20 year life (or more) for the thermal systems, but will still have extended life providing electricity even if the thermal systems are decommissioned or replaced.

7.3 COST ANALYSIS AND COMPARISON

While PowerDish III (the demonstration model) was rated for 3.0 kilowatt alternating current (kWac) in electric-only mode of operation, the Infinia PowerDish 5 is rated at 7.5 kWac (electric-only mode); 2.5X the rated power of the demonstration model PowerDish. At the same Fort Carson location, the PowerDish 5 is expected to provide 13,750 kWh/year of electricity (versus 5500 kWh for the PowerDish III) with about 14,000 kWh/year of thermal energy expected to be used by a facility that has a good thermal energy demand (for end-use applications like space heating or cooling, process heat, and water heating).

7.3.1 Example Site: Office Use Facility

For the economic analysis, a good DNI site in the U.S. Southwest is postulated with a DNI of 7.25 kWh/m^2/day. This proposed site represents an "office" or "commercial" type environment. The electric rate is $0.11/kWh which also represents the value (avoided cost) for the electricity produced by the PowerDish. The facility electric use in the winter consumes all of the output from the PowerDish while the summer facility electric use is more than the available output from the PowerDish. The PowerDish was able to be installed near the facility with a relatively short run to the tie into the building space heating system. The water heating and the space heating systems are natural gas systems with the gas cost of $6.50/MMBTU. We will assume that the building systems convert natural gas energy at 85% efficiency into thermal energy actually used as water and space heating (high efficiency conversion). The Infinia CHP system and the building water heating, and space heating system to which it is attached, has a 20 year life. For each kWh electric that the Infinia PowerDish CHP system produces, it produces more than twice as much kWh thermal. For the purpose of this study, it is assumed that less than 50% of thermal energy available in the PowerDish CHP cooling system is actually captured and used in the office/commercial building. So, we will make the amount of thermal energy actually used by the

building equal to its kWh electric production. For the O&M costs, only the incremental cost of routine maintenance for cleaning the dish and the alternate PV systems is included in the economic study. The scheduled maintenance costs are also included for the PowerDish CHP and alternate PV/Thermal systems in the economic study. See the Final Report for full study details.

Assumptions: Please refer to Final Report.

Results: Using the Military Construction (MILCON) Energy Project Model with the parameters above and a 20 year real discount rate of 0.8% from the Office of Management and Budget (OMB) circular A-94, the PowerDish CHP Solution provides a:

- Saving-to-investment ratio = 1.24;
- Real internal rate of return of 1.89%; and
- Simple payback occurs in year 18.

Competing Technology: The competitive technology for the Office Use facility described above is a PV installation for electricity and a solar thermal installation for the thermal energy production.

At the specific site described with a DNI of 7.25 kWh/m^2/d, about 9.6 kilowatt direct current (kWdc) of solar PV (thin film) will need to be installed to provide the same electric output (20,044 kWh/year) to the facility as the PowerDish CHP system. The installed cost for a small PV system at the commercial site is about $2.50/watt direct current (Wdc) or about $24,000 for the installation needed to produce 20,044 kWh per year (about the same installed cost as the PowerDish CHP system). The solar thermal system selected and installed will be a low or medium-temperature collector system that will need to provide 40,000-45,000 kWh (~136-150 million BTU/year) hot water at ~60EC to the heat exchanger to the building system in order to have about 20,044 kWh (68.4 million BTU/year) used by the building. This system will require solar collectors, a heat exchanger, pump, and associated piping and controls. At 7.25 kWh/m^2/day DNI (2646 kWh/m^2/year), we need to have at least 16 m^2 (about 8 x 2 m^2 collectors) to collect enough solar radiation. At 70% efficient for getting solar energy into the liquid heat loop, we need about 23 m^2 of solar collectors installed (with piping, heat exchanger, pump and controllers). Eight collectors (2 m^2 each) with the associated piping, heat exchanger, pump and controls for a closed loop heating system is estimated to cost about $20,000 installed (ref: www.jc-solarhomes.com). This closed loop heating system is linked to the building water heating and space heating systems loop that carries the heat from the closed-loop solar thermal system to the building thermal system and its water and space heating applications. Because we have matched the PowerDish thermal production with the installed solar thermal system, the cost for the building thermal system and applications is the same as for the PowerDish CHP application: $20,000.

Summary Inputs:

- PV System: 9.65 kWdc PV system installed: $24,000
- Solar Thermal System: 16 m^2 installed with exchanger, pump and controls: $20,000
- Building thermal loop with water and space heating applications: $20,000
- Total investment: $64,000 (without consideration of rebates or incentives)

We make a simplifying assumption that the PV System plus the Solar Thermal System O&M costs are the same as the PowerDish CHP. As with the base case conditions, it is assumed that a salaried maintenance personnel cover the facility and take on the mirror/PV panel cleaning duties. The incremental cost for cleaning the dish or the panels is $100/year. The PV system will need to have the PV panels washed/cleaned periodically and on a similar schedule as the PowerDish. Also, the PV system will need to have the inverter maintenance performance on a similar schedule as with the PowerDish. The Solar Thermal system will need to have pumps, fans, sensors, fluid change-out, and other such hardware maintained over the life of the system. So, for simplicity we have made the PowerDish equal to the PV and Thermal system maintenance costs at the rate of $250/year (this is a conservative simplification as the PowerDish maintenance is expected to be less over the lifetime). Then, the main difference between the current solar PV + solar thermal solution versus the PowerDish CHP solution is the initial installed cost.

Evaluated in the same MILCON Energy Project model as the PowerDish CHP solution and with the same OMB discount rate of 0.8%, the PV-Solar Thermal Solution with the assumptions but has a savings to investment ratio (SIR) of 0.85; an adjusted internal rate of return (AIRR) of 0.02%; and a simple payback never reached in the study period. To break even with SIR of 1.0, the total initial investment of this solution needs to be reduced to $54,660 (a $9340 reduction).

Table 8 summarizes the important costs for the PV and PowerDish CHP solutions for the "Office/Commercial Use Facility."

Table 8. Important costs for implementing the PowerDish CHP versus PV-solar thermal.

Cost Element	Estimated Costs for Future PowerDish CHP Implementation	Estimated Costs for Current PV-Solar Thermal Implementation
Hardware capital costs	$15000 (PowerDish 5 (7.5kW) with heat exchanger) + $10,000 (in-building application hardware) = $25,000	$9600 (9.6kW Thin film PV with inverter) +$10,400 (Solar Thermal system: 68 MMBTU) +$10,000 (in-building application hardware) =$30,000
Installation costs	$10,000 (installation of PowerDish) + $10,000 (installation of in-building systems) = $20,000	$96,000 (installation cost of PV system) +$10,000 (installation of solar thermal system) +$10,000 (installation of in-building systems) = $34,000
Consumables	Water: 60 gallons/year	Water: 60 gallons/year
Facility operational costs: • **Electric cost** • **Energy cost for thermal loads**	• Electric: 20,044 kWh per year @$0.11/kWh (average) = $2205/year • Thermal: 68.4 MMBTU/year use @85% gas to thermal use conversion @$6.50/MMBTU = $523/year	• Electric: 20,044 kWh/year @$0.11/kWh (average) = $2205/year • Thermal: 68.4 MMBTU/year use @85% gas to thermal use conversion @$6.50/MMBTU = $523/year

Table 8. Important costs for implementing the PowerDish CHP versus PV-solar thermal (continued)**.**

Cost Element	Estimated Costs for Future PowerDish CHP Implementation	Estimated Costs for Current PV-Solar Thermal Implementation
Maintenance	$100/year for mirror cleaning (incremental costs to salaried facility maintenance personnel) plus scheduled maintenance reserve of $250/year	$100/year for mirror cleaning (incremental costs to salaried facility maintenance personnel) plus scheduled maintenance reserve of $250/year
Estimated salvage value	10% of initial cost	10% of initial cost
Hardware lifetime	20 year	20 year
Operator training	Incremental: minimal	Incremental: minimal

Our example is for a "very good" DNI site. Generally, as the opportunity site moves to higher DNI areas, the PowerDish CHP solution is even better than the current PV-Solar Thermal solution. And, as the site conditions are closer to 5.0 kWh/m^2/year (69% of the example site), the PV-Solar Thermal solution will be more near an equivalent solution. Electric production is most affected by the DNI and is the more dominant economic factor in the solution choice. However, there are some offsetting conditions to this general trend, namely, that as the DNI gets lower, if it is due to latitude and has cooler winters, the value of the winter space heating will go up. Also, as the DNI goes to higher values (sunnier climate), the need for space heating may go down substantially. It may be that additional investment is needed for heat driven cooling systems, which may be considered for hot water during summer months in these high DNI areas.

Overall, the PowerDish CHP solution should be considered anywhere a PV with solar thermal solution is considered, as it could prove to be a superior solution.

8.0 IMPLEMENTATION ISSUES

Among the issues encountered during the year-long demonstration period, the PowerDish system experienced periods of unplanned outage as well as an Infinia imposed power output reduction strategy that was adopted in order to improve PowerDish CHP survival during high heat flux changes under unattended, autonomous operation.

8.1 DEMONSTRATION ISSUES

There were several events that occurred during the course of the demonstration that are of note for future use of this, and other similar technologies within DoD.

- Upon initial installation of the system Infinia was unable to connect the PowerDish system to the Fort Carson electrical grid. This grid interconnection issue was solved with a software upgrade.
- As described several times in the report, Infinia imposed a “solar heat reduction” strategy to add some operating margin for the PowerDish in order to avoid “over stroke” events during periods of high solar irradiance and rapid changes in the irradiance such as when the system moves from cloud to full sun conditions. Over Insolation (OI) is a controlled PowerDish operational method where sunlight is intentionally spilled beyond the aperture as a way to shed excess input energy. Infinia implemented OI during most of test period in order to operate in unattended, autonomous mode without risking PowerDish CHP system damage. This OI control scheme reduced the anticipated combined power output of the system.
- The predominant issue with the CHP demonstration overall was the low level of heat delivery to the building. During the early months of the demonstration, the daily operation showed, on average, 18% of the thermal energy available at the engine was getting to the building systems. This low heat transfer was first observed during the December 2011 testing and was initially thought to be largely due to thermal losses occurring between the PowerDish engine and the building thermal systems. Subsequent testing on site provided insight into a number of contributors that caused lower than expected thermal energy delivery.

8.2 LOW ENERGY DELIVERY TO BUILDING SYSTEMS: LESSONS LEARNED

In conclusion, the lessons learned for improving the CHP application in future projects can be summarized as:

1. A low-temperature heat exchanger is needed to allow for more heat to be transferred to the building;
2. The solar CHP system should be kept physically close to the building and POU applications to minimize losses;
3. The thermal heat should be taken directly to the POU applications first and then to thermal storage to maximize the utilization of available thermal energy; and

4. An improved design PowerDish that enables 70EC generator cooling loop temperature should be used to improve efficiency of heat transfer to building and POU applications.

APPENDIX A

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